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Flutter Analysis of the Shuttle Tile Overlay Repair Concept

*Kim S. Bey, Robert C. Scott, and Robert E. Bartels
Langley Research Center, Hampton, Virginia*

*William A. Waters and Roger Chen
Lockheed Martin Space Operations, Hampton, Virginia*

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Langley Research Center
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Abstract

The Space Shuttle tile overlay repair concept, developed at the NASA Johnson Space Center, is designed for on-orbit installation over an area of damaged tile to permit safe re-entry. The thin flexible plate is placed over the damaged area and secured to tile at discreet points around its perimeter. A series of flutter analyses were performed to determine if the onset of flutter met the required safety margins. Normal vibration modes of the panel, obtained from a simplified structural analysis of the installed concept, were combined with a series of aerodynamic analyses of increasing levels of fidelity in terms of modeling the flow physics to determine the onset of flutter. Results from these analyses indicate that it is unlikely that the overlay installed at body point 1800 will flutter during re-entry.

Introduction

The Shuttle tile overlay repair concept, developed at the NASA Johnson Space Center, is designed for on-orbit installation in the event of damage to the thermal protection system tiles to enable safe re-entry. It consists of a thin flexible C/SiC plate backed with a layer of fibrous insulation that covers the area of damaged tile. The plate and underlying gasket are secured to the tile with auger-like fasteners through holes at discreet locations around the perimeter of the plate. The tile overlay repair concept installed on an array of tiles is shown in Figure 1. As part of the development effort, a series of panel flutter analyses were performed to determine whether the concept met the required safety margins for the onset of flutter.

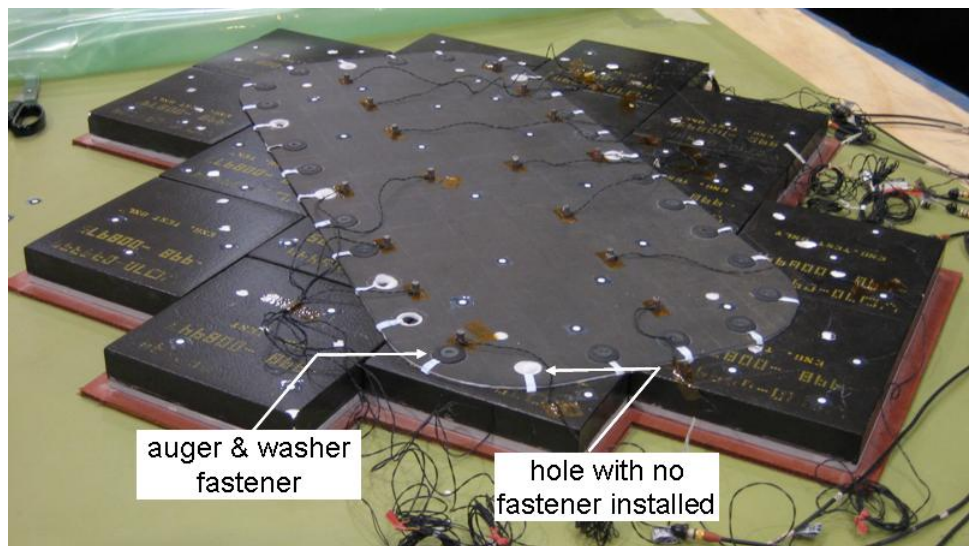


Figure 1 - Tile overlay repair concept installed on a tile array.

Panel flutter is a self-excited, dynamic-aeroelastic instability of thin plate or shell-like components of a vehicle occurring frequently, though not exclusively, in supersonic flow. Flutter is caused and maintained by interaction among the aerodynamic, inertial, and elastic forces of the system. [1] During panel flutter, the amplitude of the oscillatory out-of-plane motion increases exponentially with time, but is usually limited by the effects of in-plane stresses

and structural nonlinearities. At subsonic speeds, the instability is usually in the form of static divergence or aeroelastic buckling. [2] The onset of flutter is characterized by the dynamic pressure at which the amplitude of oscillatory motion grows with time. The accuracy of the prediction of the flutter dynamic pressure is determined by the accuracy of both the aerodynamic and structural analyses used to predict the aerodynamic forces on and structural response of the oscillating plate, respectively. To avoid flutter, a panel should be designed so that the flutter dynamic pressure is greater than the local dynamic pressure experienced in flight. The requirement for the Shuttle includes a 1.5 factor of safety on the flight dynamic pressure of 375 psf, thus requiring that the flutter dynamic pressure of the overlay panel be greater than 563 psf.

A number of vibration and flutter analyses of the overlay panel were performed to determine the onset of flutter and to quantify uncertainties in the analyses. The series of analyses are described and numerical results are presented in this paper.

Structural Model and Modal Analyses

The overlay plate is constructed of a C/SiC composite material and is 15 inches wide by 25 inches long with a thickness of 0.04 inches. A series of holes are placed along the perimeter of the plate, as shown in Figure 1, to accept the auger and washer fasteners that attach the overlay repair to Shuttle tile. For the structural analysis, material corresponding to the holes was not removed from the finite element model. The material properties used for the C/SiC material were taken from experimental data obtained for a 0.13-inch thick plate of similar construction [4]. C/SiC is a nonlinear material in the sense that the stress-strain curves for the material are linear only for small strain. Additionally, the stress-strain behavior is different for compressive and tensile loading. The linear structural analysis for vibration modes assumed an orthotropic material with a modulus that is the average of the modulus obtained from compression and tension tests at 2000⁰F given in Reference 4.

A free vibration analysis of the plate was performed to validate the finite element model by comparison with experimental data. Then a modal analysis of the plate in an installed configuration was performed by constraining the model at the auger locations. The mode shapes from the modal analysis of the constrained plate were used in the flutter analysis.

Free Vibration of the Overlay Plate

A free vibration analysis of the plate was performed to validate the finite element model by comparison with experimental data. The free vibration analysis of the plate was performed using MSC.NASTRAN SOL 103 with the finite element mesh shown in Figure 2. All degrees of freedom for a single node corresponding to a corner auger hole were constrained to eliminate rigid body motion, as indicated in Figure 2. Structural damping of the plate was neglected. The natural frequencies of the first four modes obtained from the analysis are compared to those obtained from a free vibration experiment [5] in Table 1. The correlation between the analysis and experiment suggests that the finite element mesh and material properties used in the model are adequate.

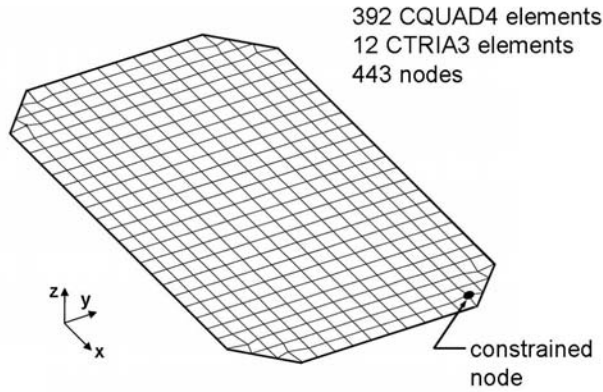


Figure 2 - Coarse finite element mesh used for free vibration analysis.

Table 1 - Comparison of free vibration frequencies obtained with analysis and experiment

Mode	Frequency (Hz)	
	Analysis	Experiment
1	19.4	16.4
2	20.9	20.5
3	47.4	40.6
4	51.6	46.7

Modal Analysis of the Installed Overlay Plate

A modal analysis of the installed overlay plate was performed for use in the flutter analysis. A simplified structural model which neglects structural damping of the plate, damping associated with the underlying gasket and tile, and plate curvature and resulting stress due to compression of the gasket during installation was used. These factors tend to reduce the susceptibility of the panel to flutter, therefore, neglecting them results in a conservative analysis.

For an actual installation of the overlay plate, it is likely that some of the auger holes will lie over inter-tile gaps or near tile edges. Augers will not be installed into such holes as illustrated in Figure 1. Since the location of uninstalled augers is installation location specific, it was assumed that all augers are installed for the modal analysis. In the finite element mesh, nodes are placed at locations corresponding to the center of the auger holes. The auger attachment to the tile is modeled as a rigid point constraint, meaning all degrees of freedom are constrained for the nodes corresponding to hole centers. The constrained nodes corresponding to the auger locations are denoted by ellipses on the coarse finite element mesh shown in Figure 3.

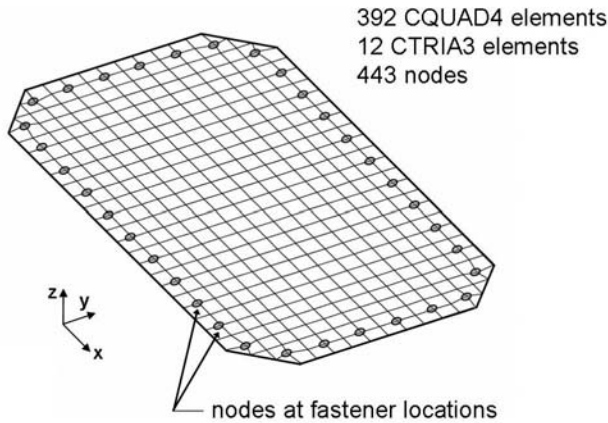


Figure 3 – Coarse finite element mesh with constrained nodes used for modal analysis of installed overlay plate.

The modal analysis of the constrained plate was performed using MSC.NASTRAN SOL 103 [3] to determine the normal mode shapes to be used in the nonlinear flutter analysis. A mesh convergence study was performed to determine the sensitivity of the first natural frequency of the constrained plate to mesh size. The mesh convergence study consisted of a sequence of modal analyses performed with increasingly refined finite element meshes, starting with the mesh shown in Figure 3. The results of the mesh convergence study in Figure 4 show that the first mode frequency decreases as the number of nodes in the mesh increases, and that convergence isn't reached with a mesh containing 26,539 nodes. A decrease in the predicted frequency of 4% is obtained when elements in the 26,539-node mesh are subdivided to obtain a 105,557-node mesh. To achieve a balance between analysis complexity and accuracy, the vibration modes obtained with the 26,539-node mesh are used in the nonlinear flutter analysis described below. The first 25 modes having frequencies between 64 and 670 Hz are used. The first four mode shapes obtained with the 26,539-node mesh are shown in Figure 5.

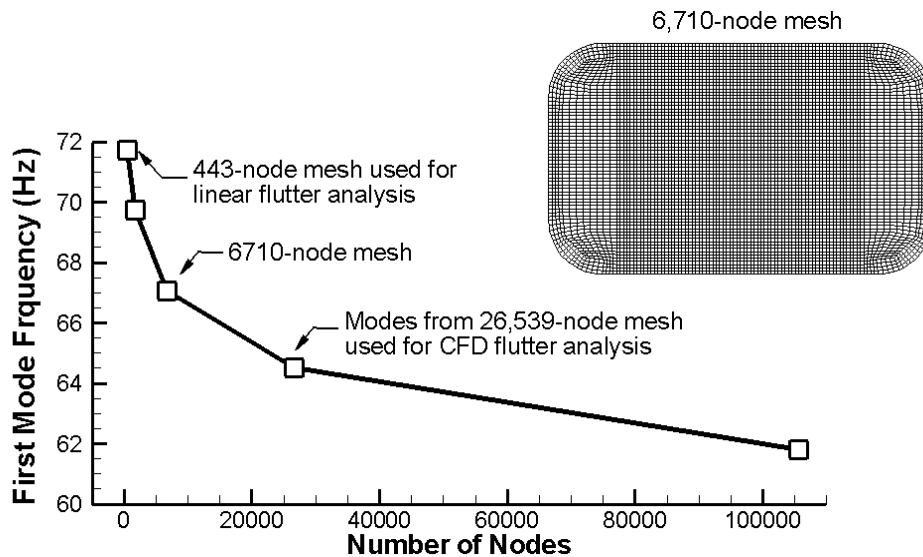


Figure 4 - Convergence of the first natural frequency of the constrained plate with mesh refinement.

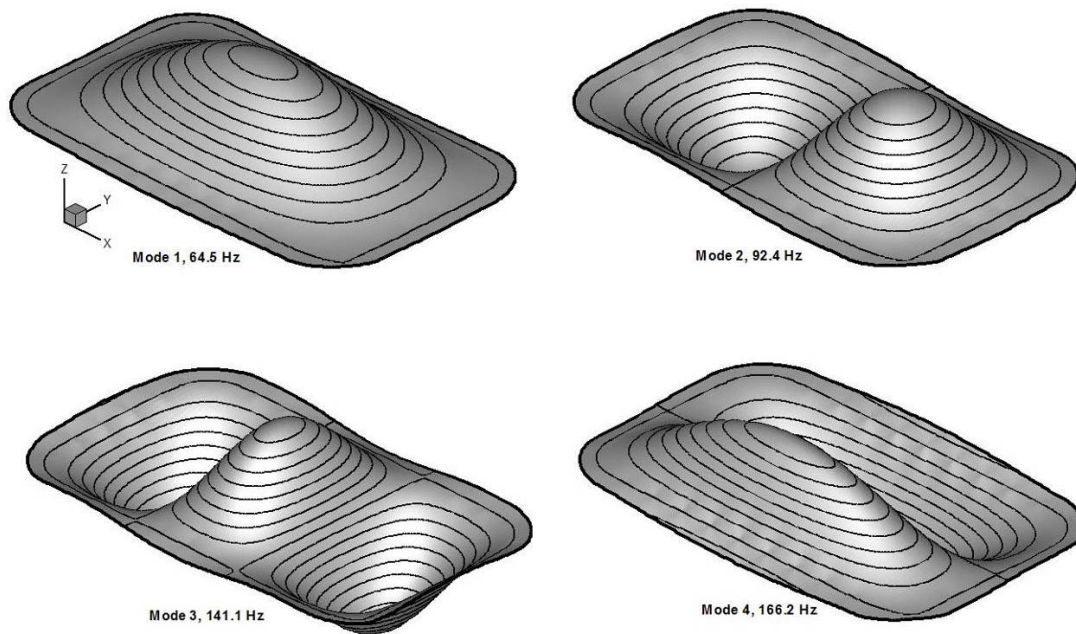


Figure 5 - First four mode shapes for the constrained plate obtained with a 26,539-node mesh.

Flutter Analysis using Linear Aerodynamic Theory

The procedure used for a preliminary flutter assessment combines a linear flutter analysis performed at flow conditions of Mach 2 with correlations from classical design criteria [2] for extending the results to flow conditions of Mach 1.

A linear flutter analysis was performed for Mach 2 flow aligned with the long axis of the panel, the flow direction for which the panel is most susceptible to flutter. NASTRAN Version 2005 SOL 145 [3] was used for the flutter analysis. It uses a (linear) quasi-steady two-dimensional aerodynamic theory to predict the aerodynamic forces on an oscillating plate. In particular, first-order piston theory was used and is believed to be reasonably accurate for Mach 2 flow.

The finite element mesh shown in Figure 3 was used for the structural portion of the flutter analysis. To determine the sensitivity of the onset of flutter to the auger attachment constraints, several constraint conditions at the auger fastener locations were analyzed. The resulting flutter dynamic pressure predictions are summarized in Table 2. The fastener constraint conditions listed in the first column of Table 2 represent the set of constraints applied to the nodal degrees-of-freedom (DOFs) for each fastener - three translational DOFs u , v , and w and three rotational DOFs θ_x , θ_y , θ_z about the x -, y -, and z -coordinate directions respectively. A value of 1 indicates that motion associated with the degree of freedom was constrained and a value of 0 indicates that it was free. Therefore, a constraint condition 001000 means that only out-of-plane displacements, those in the z -direction, were constrained at the fastener locations. The cases are listed in Table 2 in order of increasingly constrained motion, and hence, in order of increasing flutter dynamic pressure. The case with all DOFs constrained is believed to most accurately represent the fastener-tile attachments. For all constraint cases, a considerable margin exists between the

predicted flutter dynamic pressure and the 563 psf requirement.

Table 2 – Summary of results from a NASTRAN flutter analysis (SOL 145) of a simplified model of the installed overlay panel at Mach 2 flow conditions.

Fastener Constraints $uvw\theta_x\theta_y\theta_z$ (1 = fixed, 0 = free)	Flutter Frequency (Hz)	Mach 2 Flutter Dynamic Pressure (psf)
001000	63	1050
111000	66	1056
111111	100	1352

Correlations from Reference 2 are used to extend the flutter analysis results to Mach 1 flow conditions. The correlation provides a multiplicative “knockdown” factor that is applied to the flutter dynamic pressure obtained from the linear flutter analysis at Mach 2. The correlation is based upon experimental data obtained for a plate with an aspect ratio of 2 with completely clamped edges. The flutter dynamic pressure at Mach 1, obtained from the correlation, is listed in Table 3. The constraint case 111111 in the last row of Table 3 most closely represents the experiments upon which the correlation is based, but it is likely that the actual flutter dynamic pressure is less than the correlated values. Since the flutter dynamic pressure from the correlation is less than 563 psf (the flight dynamic pressure with the required safety factor of 1.5 applied), panel flutter cannot be eliminated as a design concern for the overlay panel using this simplified analysis.

Table 3 - Summary of flutter results for a simplified model of the installed tile overlay panel at Mach 1, based on empirical correlation² of Mach 2 predictions.

Fastener Constraints $uvw\theta_x\theta_y\theta_z$ (1 = fixed, 0 = free)	Correlated ² Mach 1 Flutter Dynamic Pressure (psf)
001000	291
111000	293
111111	375

According to classical literature on flutter [1], three-dimensionality of the flow becomes important when $\sqrt{M^2 - 1} \frac{\ell}{w} < 1$, where ℓ is the length of the panel in the direction of the flow and w is the width. For the overlay panel, this parameter suggests that three-dimensionality of the

flow may be important for $M < 1.2$. Since the flutter analysis at Mach 2 is based on two-dimensional flow, and the empirical correlation is based on boundary conditions that are “stiffer” than those of the installed overlay panel, a flutter analysis using computational fluid dynamics (CFD) is required to reduce uncertainties in the aerodynamic portion of the flutter analysis.

Flutter Analysis using Nonlinear Aerodynamic Theory

To incorporate more realistic physics into the flutter analysis, a nonlinear aerodynamic analysis, specifically CFD solutions of the Euler and Navier-Stokes equations, was coupled with the simplified linear structural model for Mach 1.1 and Mach 2 flow conditions. The Euler equations describe three-dimensional inviscid flow and capture the effects of an oscillating plate on the flow, including shocks and expansions. The Navier-Stokes equations describe three-dimensional viscous flow which adds the effects of the boundary layer near the surface of the plate.

The CFD code CFL3Dv6 [6] was used for the flutter analysis. The CFL3Dv6 code solves the time-dependent conservation law form of the Reynolds-averaged Navier-Stokes equations using a finite-volume approach. Upwind-biasing is used for the convective and pressure terms while central differencing is used for the shear stress and heat transfer terms. Implicit time advancement is used with the ability to solve steady or unsteady flows. Sub-iteration and multi-grid capabilities are available for improved accuracy and convergence acceleration.

The typical procedure for using CFL3D for flutter analysis is to obtain a static aeroelastic solution prior to running a solution to determine dynamic stability. This is done by using artificially large values of structural damping in the analysis where CFL3D is run until it converges. This step is unnecessary for the inviscid analysis as the static aeroelastic solution has zero panel deflection and the flow field has free stream conditions throughout. For the viscous analyses, the pressure difference across the panel is not zero, and a static aeroelastic solution must be obtained for each dynamic pressure.

Once the appropriate flow field and static aeroelastic solution has been established, the dynamic analysis is performed. The structural damping is set to a realistic value (zero in this case) and the generalized coordinates are given small initial velocities. The analysis is run until dynamic aeroelastic stability can be established: if the generalized coordinate values converge to a finite value then the system is stable, but if they grow with time, then the system is unstable. For each freestream flow condition of interest, flutter onset is determined by varying the dynamic pressure until the system becomes unstable.

Inviscid Flutter Analysis Results and Discussion

For the flow field grid, the overlay panel is modeled as a flexible section of a larger rigid flat plate. Only one grid point upstream of the flexible panel is required, resulting in the grid shown in Figure 6. Time histories of the modal amplitudes from the flutter analysis at Mach 2 with dynamic pressures of 800 psf and 900 psf, are shown in Figure 7. For a dynamic pressure of 800 psf, the amplitudes decay with time, and are therefore stable. For a dynamic pressure of 900 psf, the amplitudes are growing with time, and therefore, are unstable. Note that the first and second modes are involved in producing flutter. The third mode contributes only after the onset of flutter, suggesting weak participation. Thus, the dynamic pressure associated with panel flutter

onset at Mach 2 is between 800 and 900 psf. The inviscid flutter analysis for Mach 1.1 flow conditions predicted the onset of flutter at a dynamic pressure of 275 psf, significantly lower than the required 563 psf. Therefore, panel flutter cannot be eliminated as a design concern for the overlay panel using an inviscid analysis. The assumption of inviscid flow results in velocities near the surface of the plate that are larger than for the actual flow which is viscous. Results from flutter analysis using viscous flow are presented in the next section.

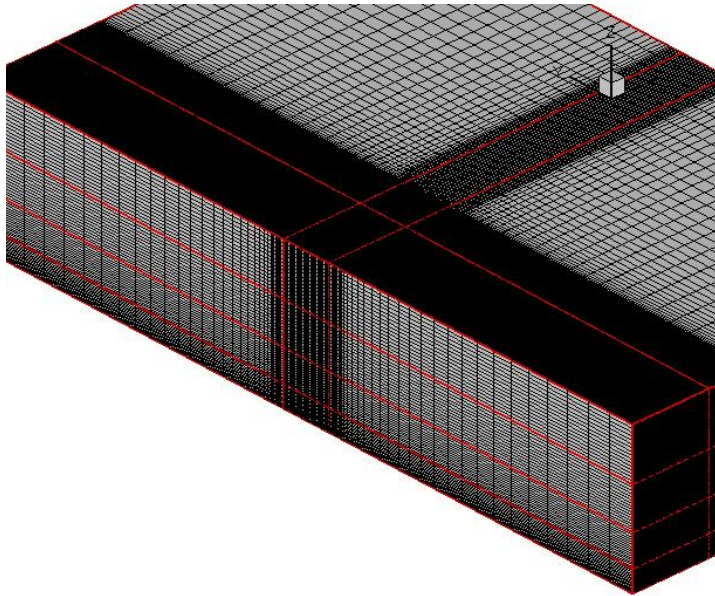


Figure 6 - Volume grid used in the inviscid panel flutter analysis.

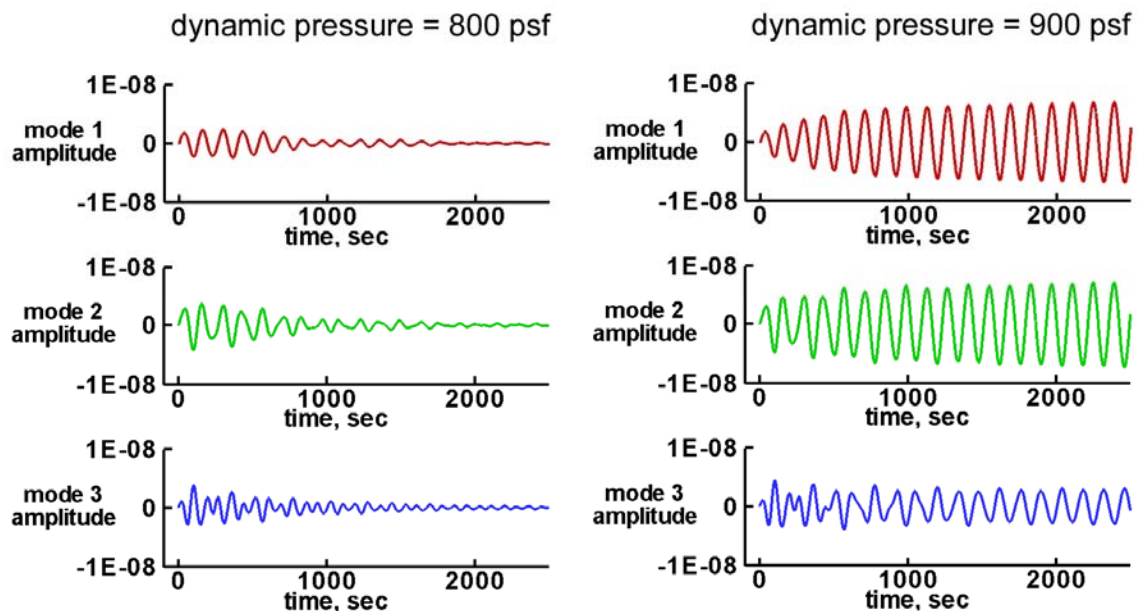


Figure 7 - Generalized coordinate time histories from the inviscid flutter analysis for Mach 2 flight with dynamic pressures of 800 psf (left) and 900 psf (right).

Viscous Flutter Analysis Results and Discussion

For the viscous analysis, the flat plate surface must be extended upstream in an attempt to match the boundary layer predicted by an OVERFLOW analysis of the flow over the entire vehicle. Thus, Mach numbers and Reynolds number roughly correspond to OVERFLOW boundary layer profile data at body point 1800 specified by the Johnson Space Flight Center [7].

For the analysis at Mach 2 flow conditions, the grid was extended upstream a distance of 860 inches. The surface grid is shown in Figure 8 with displacements corresponding to the first vibration mode applied to the panel to reveal its location in the grid. The resulting boundary profile at the patch panel leading edge for a viscous steady analysis is compared to the OVERFLOW full-vehicle boundary layer profile in Figure 9. Notice that for the Mach number approaches 1.8 in the z-direction. The CFL3D analysis was performed at a Mach number of 1.8 to match the boundary layer obtained from the OVERFLOW calculation of the entire vehicle at a Mach 2 flight (freestream) conditions. The time histories of the modal amplitudes obtained with the viscous flutter analysis at Mach 2 with dynamic pressures of 800 and 900 psf are shown in Figure 10. The system is stable at 800 psf and unstable at 900 psf, indicating a flutter dynamic pressure of approximately 850 psf. This flutter dynamic pressure is comparable to the inviscid flutter analysis prediction with acceptable margin above the 563 psf requirement.

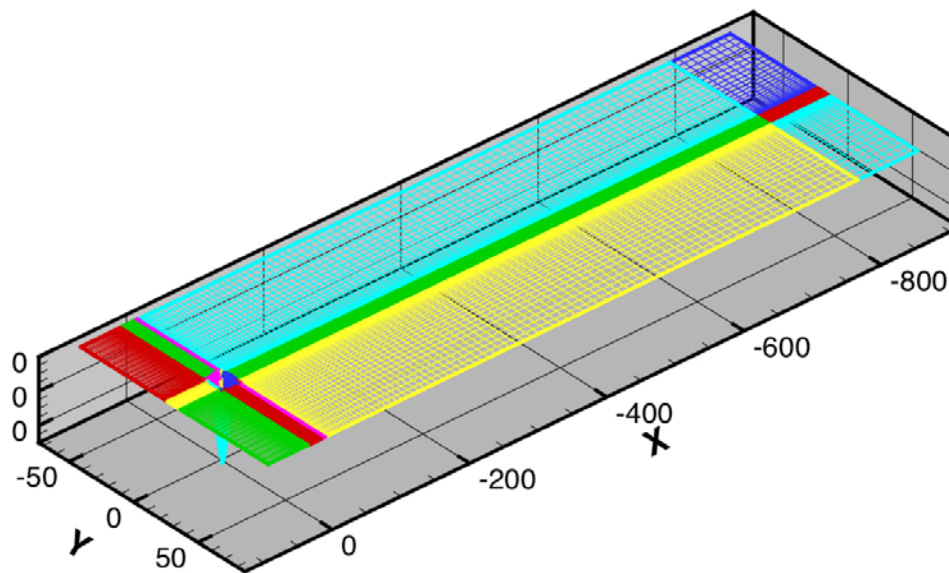


Figure 8 - Surface grid for Mach 2 viscous flutter analysis with the panel deflected to the first mode shape for clarity. The flow is from right to left.

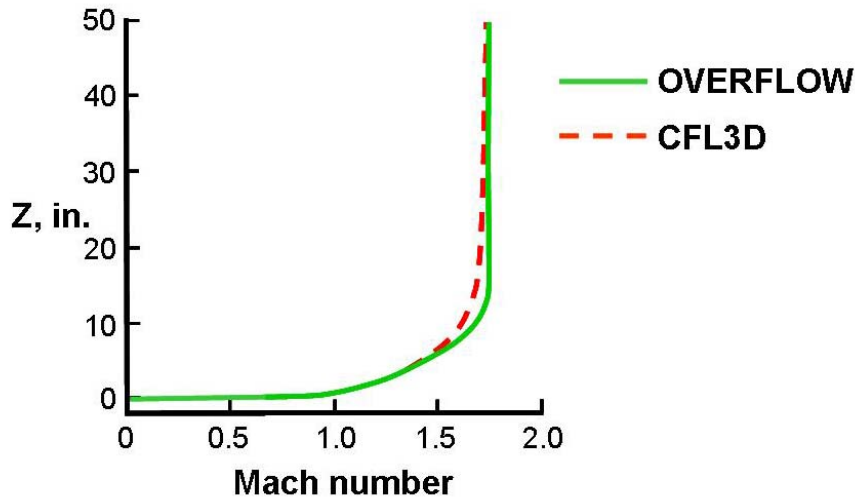


Figure 9 - Comparison of boundary layer profiles at the panel leading edge placed at body point 1800 on the vehicle for Mach 2 flow. Solid line indicates OVERFLOW solution obtained with a flow domain encompassing the entire vehicle. Dashed line indicates CFL3Dv6 solution obtained with a truncated flow domain in the vicinity of the panel.

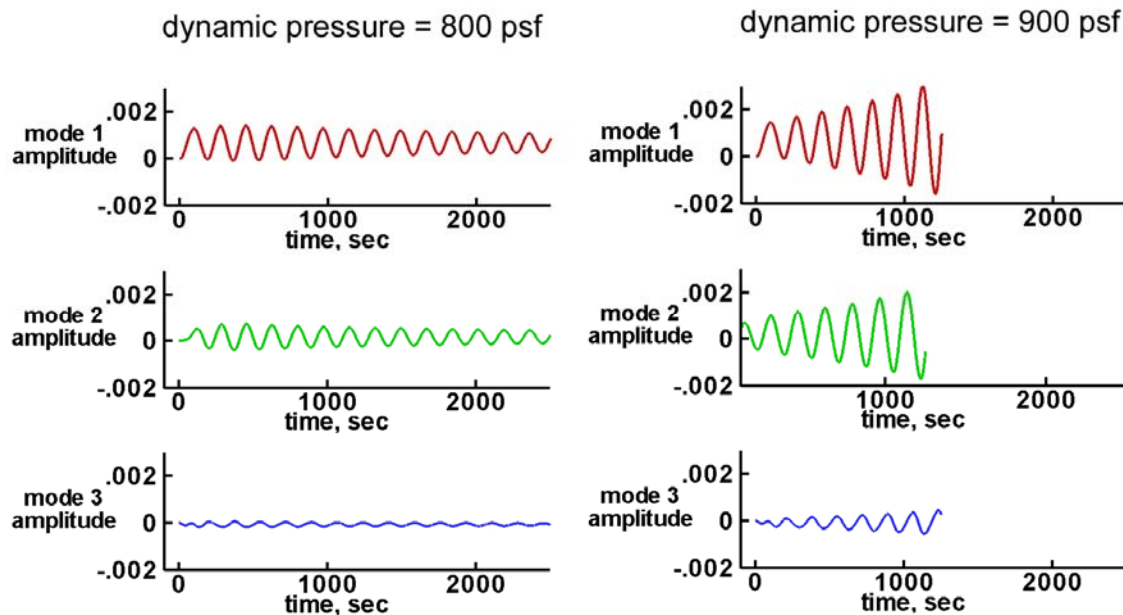


Figure 10 – Generalized coordinates time histories from viscous flutter analysis for Mach 2 flight with dynamic pressures of 800 psf and 900 psf.

In order to achieve the desired boundary layer profile for Mach 1.1 flow conditions, the grid was extended upstream of the overlay panel for a distance of 415 inches. The resulting surface grid is shown in Figure 11 with first mode displacement applied at the location of the panel. The OVERFLOW boundary layer profiles were rescaled to approach a Mach number of 1.1 to provide the target boundary layer profile for the CFL3D analysis. A comparison of the boundary

layer profiles at the panel leading edge is shown in Figure 11. Time histories of the modal amplitude show that the system is stable at a dynamic pressure of 1000 psf and unstable at a dynamic pressure of 1100 psf, indicating a flutter dynamic pressure of approximately 1050 psf - sufficient margin above the 563 psf requirement and significantly higher than the inviscid prediction of 275 psf. Based on this analysis, it is unlikely that the overlay panel will flutter if installed at body point 1800 on the Shuttle.

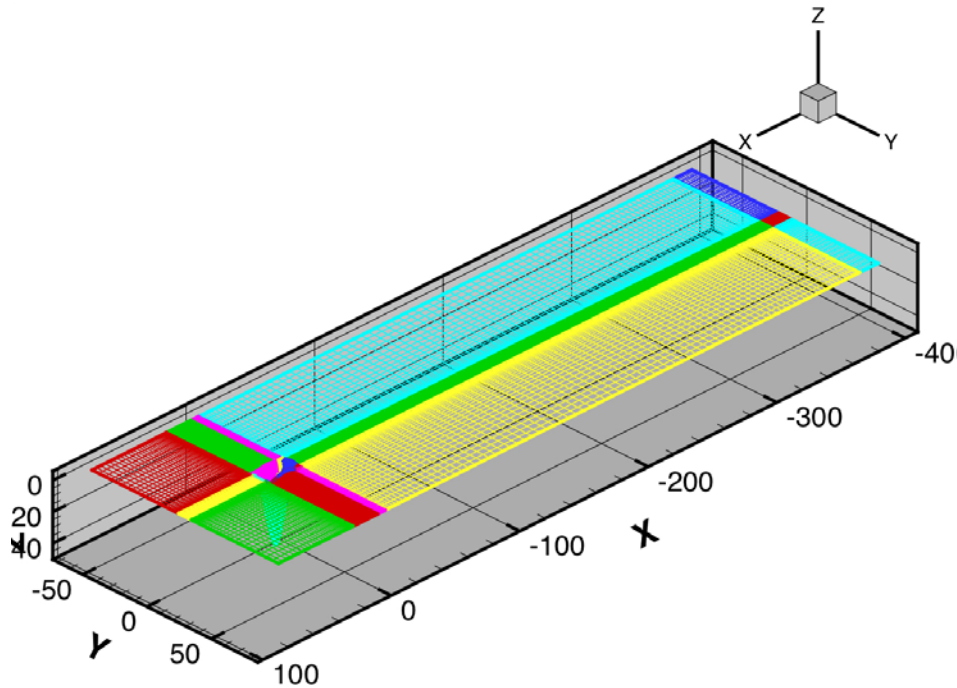


Figure 11 - Surface grid for viscous flutter analysis at Mach 1.1 with panel deflected to the first mode shape. Flow is from right to left.

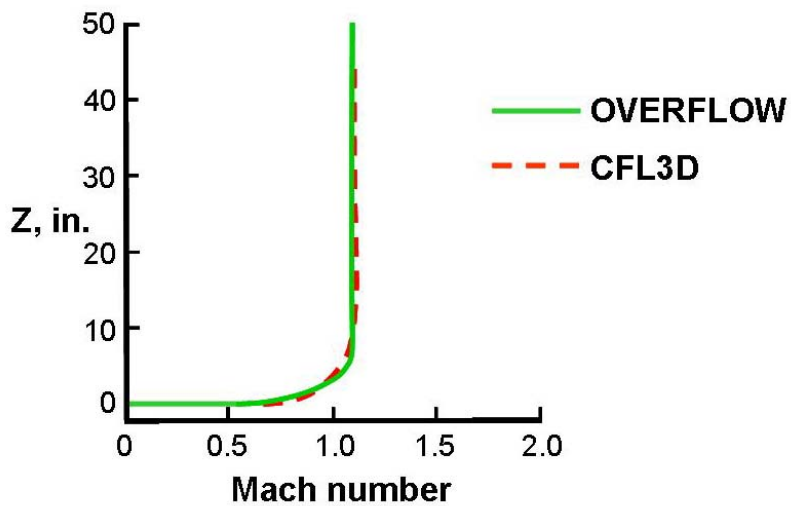


Figure 12 - Comparison of boundary layer profiles at the leading edge of overlay panel for Mach 1.1 flow.

Summary and Concluding Remarks

A comparison of the results from the flutter analyses with all degrees of freedom constrained at all auger locations is listed in Table 4. These analyses indicate that at Mach numbers of 2.0 and higher, adequate panel flutter margins exist within the shuttle flight envelope for the overlay panel installed at body point 1800. However, near Mach 1.0 empirical flutter analysis using the criteria described in Reference 2 yield inadequate flutter margins. To address this concern, flutter analyses were performed using CFL3D modeling both an inviscid (Euler) and viscous (Navier-Stokes) flow field. The inviscid analyses indicate that panel flutter onset would occur at lower dynamic pressures than had been predicted by the linear and empirical solutions; yet, the bottom line results are the same with sufficient flutter margin still remaining at Mach 2 and inadequate flutter margin near Mach 1.0. The viscous flutter analysis for Mach 2.0 was consistent with the inviscid solution. The viscous flutter analyses near Mach 1.0 indicate that the flutter onset dynamic pressure is, in fact, well outside the Shuttle flight envelope for body point 1800.

Table 4 - Flutter analysis results for increasing levels of fidelity flow physics

Analysis Type	Mach 2 Flutter		Mach 1.1 Flutter	
	Frequency (Hz)	Dynamic Pressure (psf)	Frequency (Hz)	Dynamic Pressure (psf)
Piston Theory + Correlation	100	1352	--	375
Inviscid CFL3D	75	890	61	275
Viscous CFL3D	69	850	47	1050

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